Senior Capstone Project:
A Modular Liquid Cooling system for a Li-ion Battery Pack

Team Name: LICH System

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Abstract

This paper describes the design and validation of a modular liquid cooling system for a lithium-ion battery pack to be used on forklifts built by Hyster-Yale Group (HYG). As the world's carbon pollution becomes increasingly damaging, the need for electric vehicles increases. HYG is hoping to help meet this demand by converting some of their forklifts to electric by replacing the internal combustion engine with a lithium ion battery pack. However, the seven lithium ion batteries they're using produce more heat than the system can remove with its current cooling supply. If LICH System can autonomously cool the batteries to a stable temperature even when charging, internal combustion to electric conversions can be achieved without sacrificing performance.

Background

HYG designs, engineers, manufacturers, sells, and services a comprehensive line of lift trucks and aftermarket parts. With the emergence of opportunity charging for lithium-ion batteries HYG sees the opportunity to match the performance of typical internal combustion engines. As these batteries are used in more applications it becomes apparent that a robust cooling system is required to allow the batteries to be used in high ambient temperatures environments and also have the ability to be rapidly charged and discharged.

LICH system is tasked with designing this robust cooling system and if successful, will help HYG greatly reduce carbon emissions, produce lift trucks that can be used safely indoors, lower operation costs, and reduce the downtime needed to charge the batteries.

This project is a continuation of a previous capstone project in which an air cooled system was developed. That system proved to be insufficient to effectively cool

the batteries but data gathered and components used by that team (named Cool Charge) are used by LICH system’s design.

Problem Definition and Requirements

The designed modular liquid cooling system should meet or exceed the following requirements:

Functional

- Cool batteries below 45 ¥
- Begin and end operation after batteries pass a threshold internal temperature of no more than 40 ¥
- Minimize temperature gradient across the battery pack
- Fluid fill ports must be accessible with no disassembly needed
- Fill ports must fit a ½ in. diameter funnel
- Installation time should not exceed 8 hours
- Must not interfere with battery charging

Mechanical

- Be modular so that more or less batteries can be used depending on application and performance needed
- Fit the liquid heat removal interface within the 10 mm gaps between the batteries.
- Fit within the engine bay of the forklift
    - Height <503 mm (19.76 in)
    - Width <652 mm (25.67 in)
    - Depth <272 mm (10.71 in)
- Be 150 lb. or less to not interfere with normal operation
- Not require modification of the batteries for installation
- Be able to withstand vibrations caused by normal vehicle operation
- Should operate for 12 months without maintenance and 10,000 hours without replacement

Electrical

- Shut off when not in use to minimize power consumption

- a Should be compatible with battery outlet power

Environmental

- Be able to operate in ambient temperatures of up to 50 ¥

Cost

- a Production units shall not exceed $750

Project Plan

LICH System consists of four members: Donald Funk, Tarrin Funderberg, Ryan Gonzalez and Jesus Barrera. Table 1 summarizes the primary team roles and responsibilities of each member. The team meetings with the HYG representative and client, Samuel Weiss, were held every Thursday where progress on the project and new ideas were discussed. Additional meetings were held on Tuesdays with the team advisor Matthew Swenson and team mentor Maxwell Johnson. The intended and final schedules for the project can be found in the appendix.

Team Member	**Primary roles and responsibilities**
Donald Funk	Management, CAD models and simulations
Tarrin Funderberg	Secretary, Wiki page, Construction help
Ryan Gonzalez	Correspondence, CAD models help, Construction lead
Jesus Barrera	Finance, purchasing, reports

Concepts Considered: Cooling Method

This project consists of two main components: a refrigeration system and a liquid thermal interface to the batteries. The majority of the third and fourth quarter were spent doing research on these two aspects of the project. First a cooling method was selected. The following is a summary of considered concepts for the cooling method.

Thermoelectric
This method utilizes a thermocouple and an applied voltage to move heat from one junction to the other by utilizing the phenomenon called the Peltier effect.

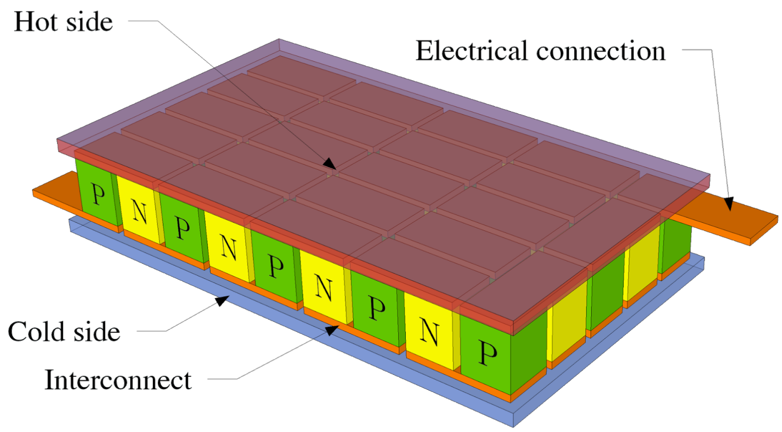

Figure 1: Thermocouple illustrating Peltier effect

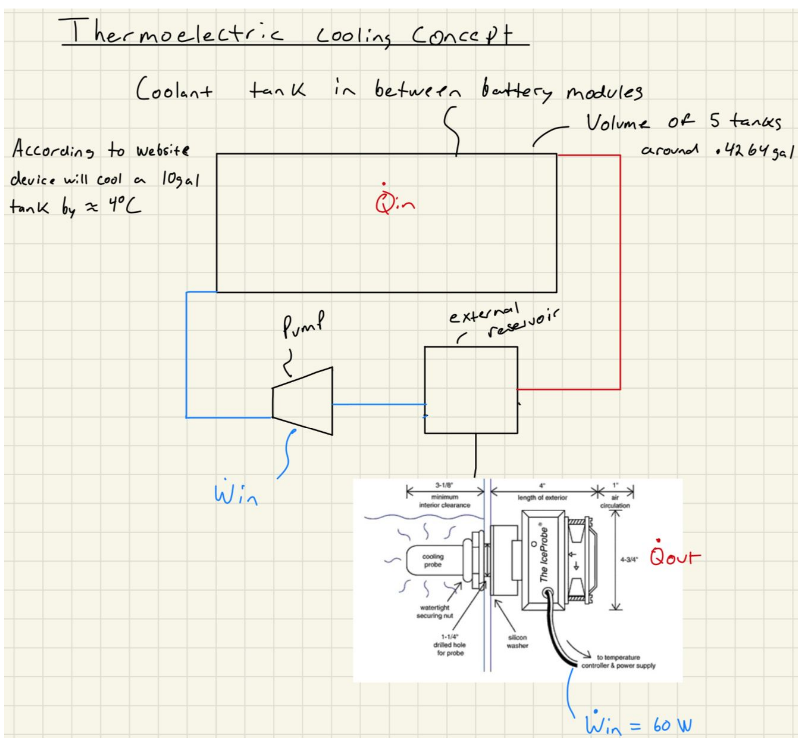

Figure 2: Thermoelectric cooling concept using a device called an iceprobe

This method utilizes no moving parts and the modules can be compact. Unfortunately this method is also inefficient and the components needed are expensive relative to

their cooling capacity. This disadvantage was a primary contributor to this design not being selected.

Vapor Absorption

This method uses a generator with a heat source to boil ammonia out of an ammonia-water mixture, creating a high pressure ammonia vapor. This vapor this then cooled with a condenser and pumped through or around the object(s) being cooled and the ammonia evaporates, taking heat away from the object(s). The ammonia then rejoins the water where it gets absorbed and compressed naturally through diffusion.

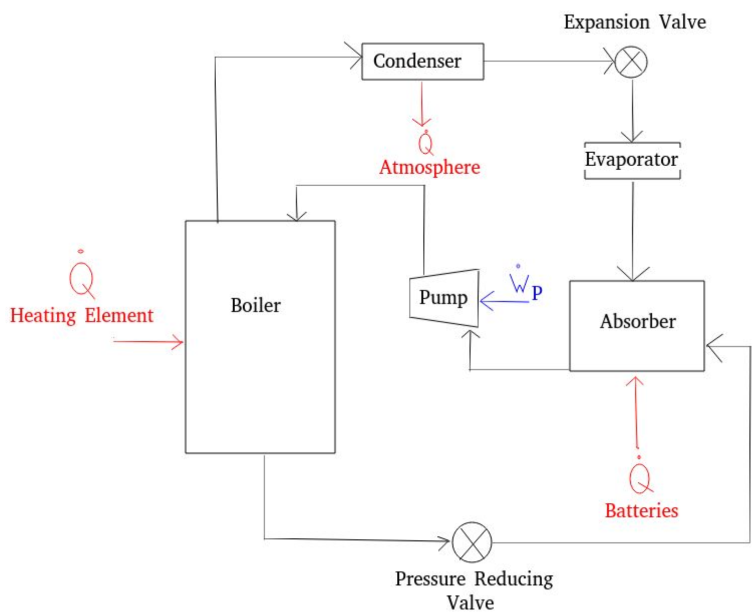

Figure 3: Vapor absorption schematic

This method was not used due to its poor coefficient of performance and the fact that at most it can only cool down to 0 ¥.

Concept Selection: Cooling Method

Vapor Compression

This is the cooling method that LICH system selected. It is the most common cooling method and is what a typical refrigerator and home air conditioning unit uses. This system is run by a compressor which takes the refrigerant in vapor form and compresses it to a superheated vapor state. The superheated vapor passes through a condenser which releases heat into the atmosphere, this process turns the refrigerant back into a liquid state. This liquid then goes through a metering device or expansion

valve and the resultant mixture of liquid+vapor passes through the evaporator which absorbs heat from the place that needs cooling. The process then begins again.

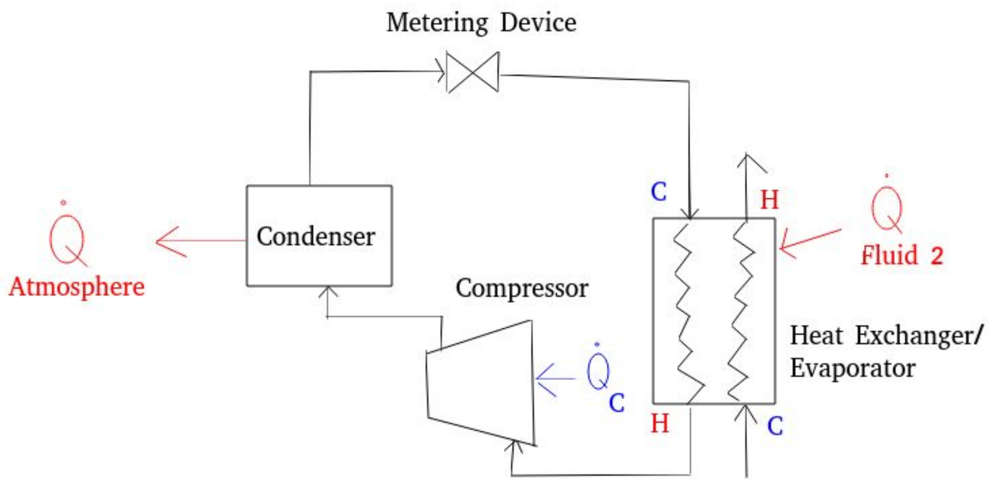

Figure 4: Vapor compression schematic

This method has a good coefficient of performance and can cool down to very low temperatures.

Hybrid System

The team decided to add a radiator to the circulating coolant loop for when the ambient temperature is not hot enough for the refrigeration system. This mode would be on most of the time. The radiator equipped with a fan would also pre-cool the glycol before it enters the heat exchanger. When the temperature reaches a certain threshold the refrigeration loop would turn on for further cooling. The following figure illustrates the two loops of circulating fluid with a plate and frame heat exchanger between the two.

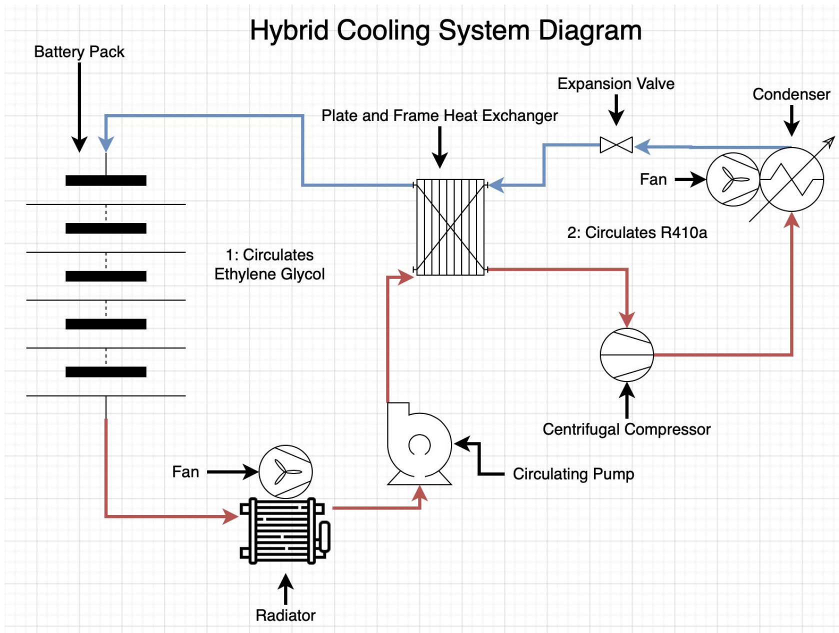

Figure 5: Hybrid Cooling System Diagram

Concepts Considered: Liquid Heat Removal interface

As previously mentioned there is only a 10 mm gap between the batteries in which the liquid thermal interface could be installed. Figure 7 shows the battery pack configuration LICH system was given to work with. It consists of 7 large batteries each with a capacity of 32 Ah. (Battery information can be found in appendix) From previous work it was determined that each battery produces 180 W of heat that needs to be extracted. (See Cool Charge thermal study in appendix)

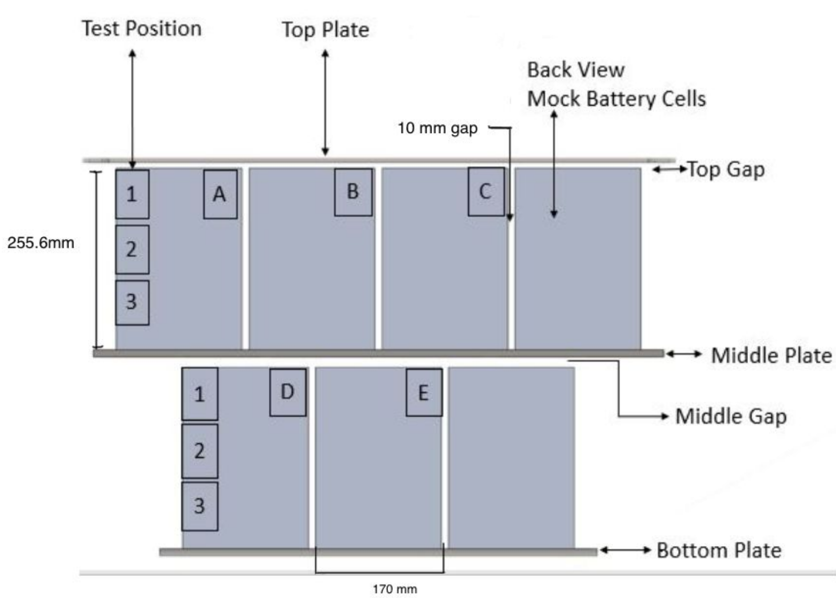

Figure 7: Battery pack configuration

It was decided early on by the team that the coolant of choice would be a 20% ethylene-glycol solution due to its high heat capacity, low cost and high availability.

The team researched three viable heat removal interfaces to run the glycol through. A reservoir, copper tubing and cold plates.

Reservoir

This could consist of a 10 mm wide tank that would be installed in between the batteries, this interface would give the highest surface area possible for heat exchange between the batteries and the glycol. Inside the reservoir patterns to direct the fluid would be made in order to ensure a uniform temperature gradient.

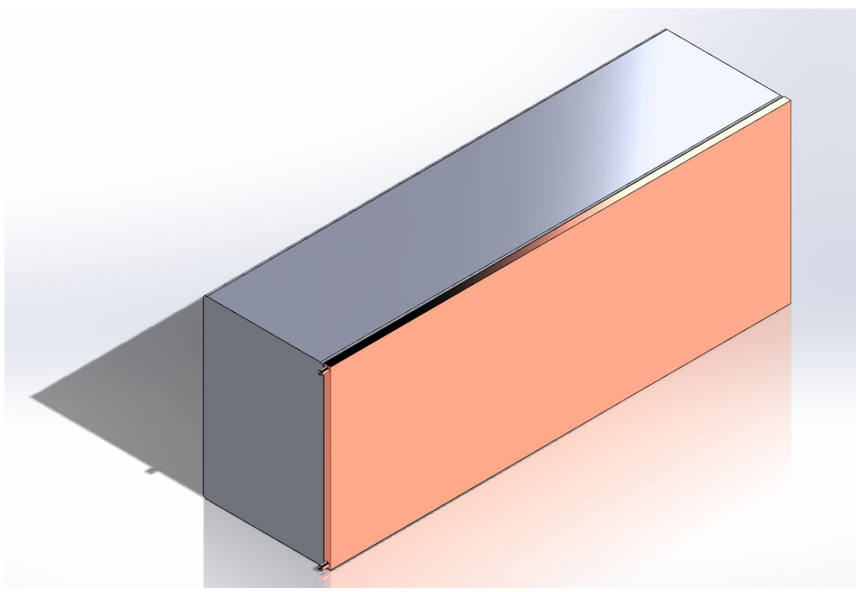

Figure 8: Reservoir concept

Cold Plates

These consist of tubes, typically copper, pressed into a milled out aluminum plate. The result is a very thin and very versatile heat removal interface that can be used in many applications. Unfortunately their complexity makes these plates expensive to manufacture and LICH system was not able to find a supplier for one with the dimensions needed for our system.

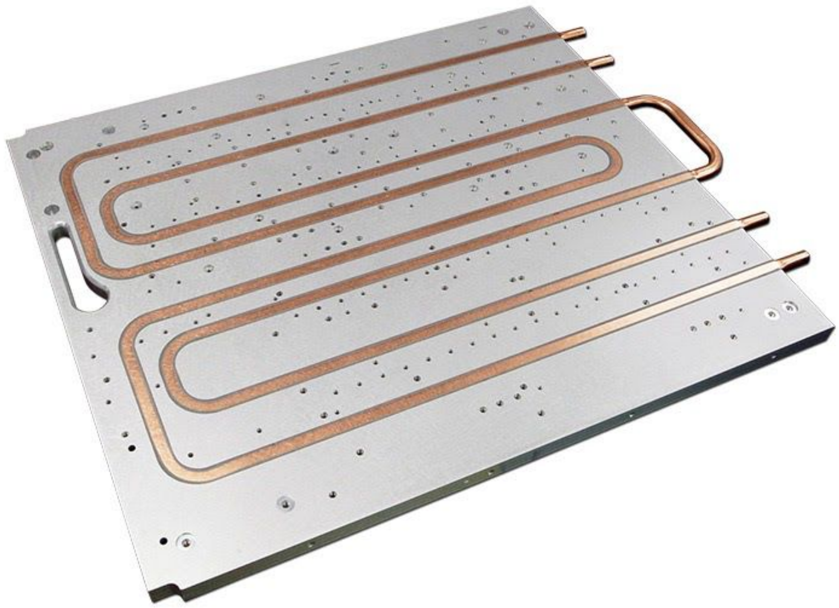

Figure 9: Cold Plate

Copper Tubing

For this interface copper tubing would be bent and pressed into a shape that covers the most surface area possible. This interface in theory would be the easiest and least expensive to manufacture.

Figure 10: Copper Tubing concept

Concept Selection: Liquid Heat removal interface

Decision Matrix for thermal interface

The team narrowed down the choice for a suitable interface down to the reservoir and the copper tubing. Manufacturing a cold plate would be far too complex and expensive for the prototype so it was eliminated as a choice. A decision matrix based on the most important design aspects the team wanted to achieve was made to choose the method that would be used.

Criteria:	Weighting:	Reservoir	Tube System
Temperature Grad	.2	4	3
Surface Area	.1	5	2
Cost of Manufacturing	.2	1	4
Cost of Materials	.1	2	3
Leaking	.1	3	5
Efficiency	.2	5	3
Manufacturing Complexity	.1	1	3
	Weighted Total:	3.1	3.3

Figure 11: Tube system vs reservoir decision matrix

Nested Tube Design

With the copper tubes being a superior choice for the prototype, the team worked on several iterations of a design. The goal for the design was to achieve the highest surface area possible and also minimizing the thermal gradient in the batteries. In order to achieve this a two tube system was selected. Figures 12-14 illustrate the design, it consists of two different tubes that are “nested”. They are made of ½” copper which is miter cut, pressed and brazed together. Each tube is attached to the side of a battery, figure 13 shows what the tubes look like inside of each 10mm battery gap.

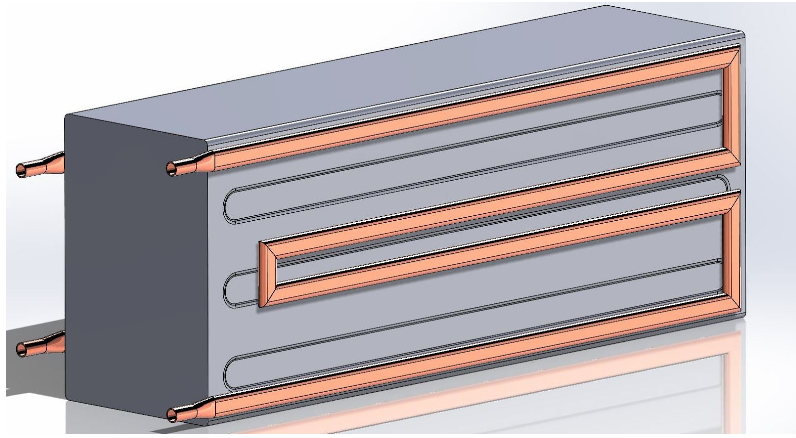

Figure 12: “Large” tube attached to the left side of battery

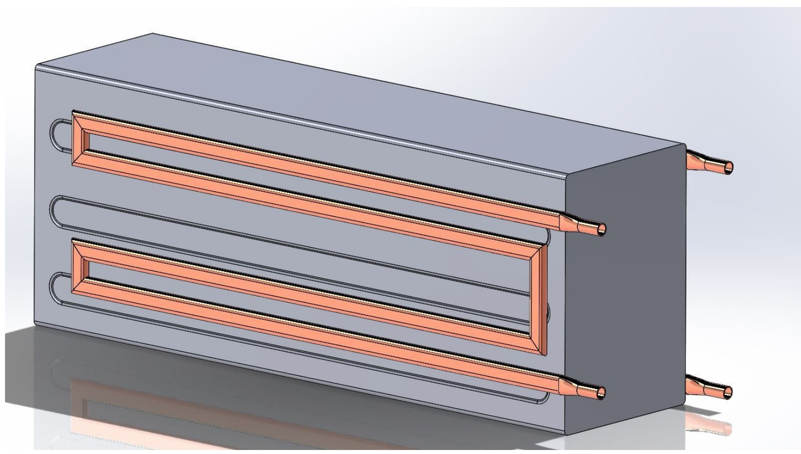

Figure 13: “Small” tube attached to the right side of battery

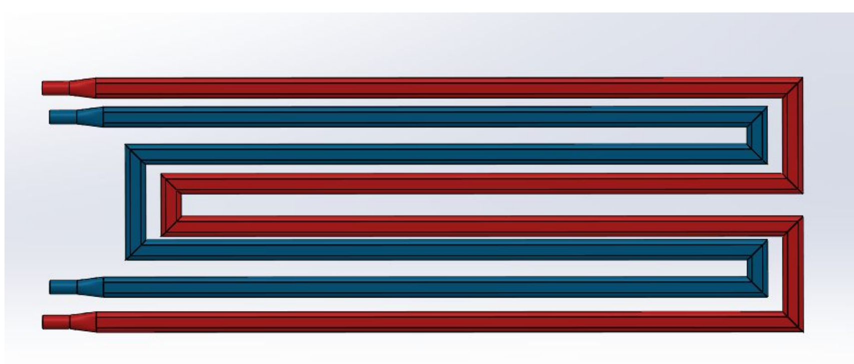

Figure 14: Nested tubes inside battery gap (large tube highlighted in red)

Another advantage of this nested tube design is that it can be modular. More tubes can be added depending on the amount of battery modules in the pack.

The reason LICH system decided to do mitre cuts and brazing for the formation of these tubes is due to limited manufacturing capability. Ideally these tubes would be made by bending a ½” copper tube to shape and then pressing it down to 9 mm in order to account for slight variations in the walls of the batteries along with the added thermal interface used to attach the tubes to the side of the batteries and increase conductivity.

Thermal Interface

In order to achieve the highest thermal conductivity and surface area possible it was decided that a thermal interface would be needed. Several options were explored including thermal tape, thermal compound and thermal pads. These options all had their own drawbacks so the team system opted to use thermal epoxy.

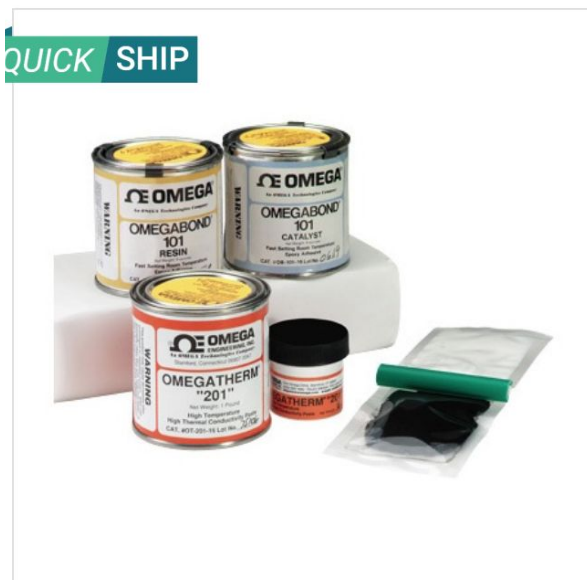

Figure 16: OMEGA thermal epoxy

This OMEGA thermal epoxy allows for the permanent mounting of the tubes to the side of each battery wall and can also be used to fill in the stamped features seen in figures 11 and 12.

System Architecture

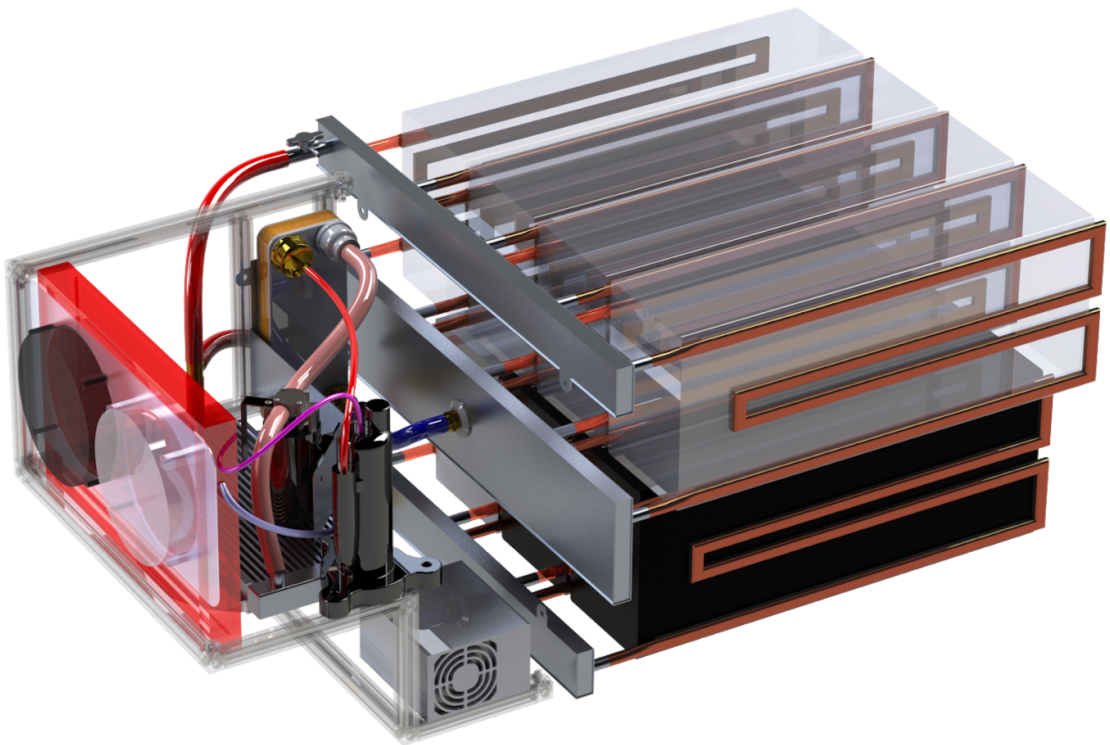

Figure 17: Final Design of system render

With the two main parts of the design selected the team then focused on integrating them. This meant selecting the needed components and packaging it all together so it would fit within the internal combustion engine bay of the forklift. The following is a summary of the major components of the prototype.

Vapor Compression Components

The vapor compression system components were salvaged from the previous year's Capstone project. They are the components from a window A/C unit and it was determined by the team that it would provide a good enough refrigeration capacity for heat removal of the batteries. The components salvaged consist of the following: